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MEASUREMENT OF THE NIGHT SKY LIGHT BACKRGROUND AT LA PALMA

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Abstract

Night sky light background is the main factor limiting the threshold of all types of atmospheric Cherenkov detectors. The intensity of this light has been measured using the single photo electron counting technique in the wavelength range of 300-600 nm for the wide angle integrating and narrow angle detectors at the site of the HEGRA experiment on the Canary Island La Palma.

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The atmospheric Cherenkov technique is the only one applicable to the Very High Energy (VHE) band (0.1-20 TeV) in gamma ray astrophysics. Only the huge detection area of typically $\geq 10^4 m^2$ allows one to measure the very faint fluxes of gamma rays from distant celestial objects ($10^{-3} - 10^{-4}$photons/$m^2\cdot$ hour) with a reasonable rate (∼one event every few minutes). Due to the strict limitations on the size of detectors for satellite born experiments the realization of any VHE gamma ray project in space is improbable, at least in the foreseeable future.

There is a growing interest in the atmospheric Cherenkov technique within the scientific community, especially after the recent detection on a high level of statistical significance of the first steady gamma ray emitter in our galaxy in the TeV energy range by the Whipple imaging Cherenkov telescope - the Crab Nebula [1] and confirmation of it by several independent groups [2, 3, 4, 5]. After the discovery of a second gamma ray emitter, this time of extra-galactic origin the BL Lac object Markarian-421 again by the Whipple group about 2 years ago [6] and a third, the pulsar PSR 1706-44 by the CANGAROO group [7], the situation became much more interesting.

A new type of detector of large angular acceptance, AIROBICC, has been designed to use the great potential of the atmospheric Cherenkov technique for UHE gamma ray astrophysics, at energies $E\gamma \geq 10$ TeV [8]. The low duty cycle of AIROBICC as compared to air shower particle arrays is easily compensated for by its lower threshold and much higher mean angular resolution of $\sim 0.2^\circ$.

One of the main drawbacks of the atmospheric Cherenkov technique is that the light of night sky (LONS) is a limiting factor when lowering the energy threshold of detectors. The amplitude fluctuations of detected LONS determine the threshold of a detector.

For the signal measurement with an atmospheric Cherenkov detector a charge sensitive analogue to digital converter (charge integrating ADC) with gate duration of ~ 30 ns is usually used. Even during such a short time a significant amount of background light is integrated together with signal, thus, depending of the design and performance of the detector, the amplitude distribution of genuine signal is more or less smeared out. This effect is more important for events which are close to detector's threshold, because, due to the power law spectra of cosmic rays, these occur most frequently and have the lowest signal content, resulting in a poor signal to noise ratio. In the subsequent analysis one has to be careful to take this into account.

LONS has several components. These are zodiacal light, integrated starlight, air-glow, aurorae, diffuse galactic light and integrated cosmic light [17]. Depending on the site and the measuring zenith angle also the man-made artificial light may contribute to LONS.

With atmospheric Cherenkov detectors one performs measurements during dark nights (between two astronomical twilights in the evening and in the morning) when the zodiacal component is very weak or negligible. Also the aurorae are rare phenomena at mid latitude places. So the main and strong components of LONS influencing Cherenkov detectors are the integrated starlight and air-glow.

Many publications quote the results of measurements of LONS intensity for a specific or limited spectral range [9, 10, 11, 12, 13, 14, 15] (for example, according to [11] , the intensity is $6.4 \cdot 10^{11} ph/m^2 \cdot sr \cdot s$ for the spectral band of 430-550 nm) or for an ill-defined

spectral range. With ground based detectors one may effectively detect the Cherenkov light from air showers in the wavelength range of ~300 to 700 nm. At wavelengths longer than 700 nm the radiance of LONS starts rapidly to increase due to the intensive emission lines of OH and H_2O bands in the upper atmosphere (see fig. 5) meanwhile the intensity of Cherenkov light drops down $\sim 1/\lambda^2$, resulting in a poor signal to noise ratio. At the lower end, below $\sim$ 300 nm the Cherenkov light undergoes strong absorption by the ozone in the air [17].

PMTs with bialkali photo-cathode give the highest yield of photo-electron (ph-e) in the detection of Cherenkov radiation compared to other types of photo-cathode materials and are widely used in the atmospheric Cherenkov detectors. These PMTs are sensitive to light in the range of 300-600 nm (the lower limit is due to the type of the glass used for the entrance window). Therefore, it is natural to measure the intensity of LONS for the spectral range of 300-600 nm.

One could try to use the results of some other measurements (see [16], for example) to recalculate the intensity of LONS for a specific place and a given detector but due to differences in location of detectors (LONS is a function of the geographical latitude, see [10] for example; also the man-made light pollution my vary) and in measuring methods and conditions such a result might have non-negligible uncertainties. The LONS influence the detectors in many ways such as the angular acceptance, the light collection area, the time response and the spectral sensitivity. The spectral sensitivity may be influenced by the transmission of filters and light guides, the reflectivity of mirrors and the spectral sensitivity of photo-multiplier tubes (PMT). Additional problems arise from the fact that some such parameters can have substantial uncertainties. Therefore, it is probably best to measure the intensity of LONS directly for a given detector at the site where it is operated.

Here we would like to define two types of intensity of LONS: for a **wide angle detector** (angular acceptance $\gg 1$ degree) where the detector integrates the direct starlight component of the LONS over substantial part of the night sky - as is the case for AIROBICC with its angular acceptance of ~1 steradian, and for a **narrow angle detector** (angular acceptance ≤ 1 degree) where the detector integrates the starlight only from the background of faint stars in a small solid angle, as for any of the 37 pixels of the imaging camera of the first HEGRA Cherenkov telescope on La Palma (the angular diameter of a single pixel is $\sim 0.4^\circ$ [21]).

According to star counts [18] in one square degree of the night sky there is on average $\sim$ 1 star with star visual magnitude $m = 8$, $\sim$ 3 stars with $m = 9$, $\sim$ 8 stars with $m = 10, \sim$ 20 stars with $m = 11, \sim$ 50 stars with $m = 12$ and so on. Recalling the angular size of a pixel of the imaging camera ($\sim 0.4^\circ \cdot 0.4^\circ$) one may conclude that on average the pixels are integrating the light from stars of $m \geq 10$. In contrast, in the case of wide angle integrating detectors stars of all magnitudes may contribute to the measured photon flux. Therefore, on should expect that wide angle integrating detectors measure higher intensity of LONS compared to narrow angle ones. For example, at large galactic latitudes ($b = 80^O$) the ratio of integrated starlight of stars with $m \geq 2$ to that of stars with $m \geq 10$ is > 2 (see [18], p. 20).

The experiment. An experiment has been carried out to measure using the single ph-e counting technique the intensity of LONS at La Palma.

Two PMTs of type FEU-130, which are used in the 37 pixel camera of the first HEGRA Cherenkov telescope, were chosen for this measurement. Actually, one of the PMTs was that *in situ* as channel #22 of the operating camera. They have a GaP first dynode, a low noise ($\sim 100-400$ pulses per second on a single photo-electron level at room temperature) and can be operated in the single ph-e mode, providing peak to valley ratio of ≥ 2.7. The PMTs have UV-glass entrance windows and Sb-Cs-K photo-cathodes and are sensitive to light in the UV-extended range of 200-650 nm. The PM tube diameter is 30 mm and the photo-cathode diameter is 25 mm.

In fig. 1 the measured quantum efficiency (QE)[2] of the used FEU-130 PMT is plotted versus the wavelength of the incident light. First detailed measurements were performed to determine the gain of the PMTs as a function of the high voltage (HV) supplied (see fig. 2). For this purpose we measured the photo-cathode and the anode currents with a picoammeter Keithley-485 under the condition of constant illumination.

During February 1993 we performed several measurements, but because of poor weather it was decided to repeat them under better conditions.

LONS for a wide angle detector. On the basis of the chosen PMTs, namely PMT #1690, a small wide angle integrating detector was constructed. The PMT was fixed at the centre of a 70 cm long metallic tube with an inner diameter of 142 mm. The distance from the entrance window of the PMT to the edge of the tube was 357 mm. A plastic diaphragm of 6 mm in diameter was placed on the entrance window of the PMT. The inner surface of the tube was covered with a mat black tape in order to suppress any stray light. The full angular acceptance of the tube was $\sim$ 23 degrees i.e. ~ 0.13 *sr*. Measurements were carried out during three nights with good atmospheric transparency. During measurements the tube was pointing to zenith. The HT of the PMT was set to -1920 V, which corresponds to an amplification of $1.0 \cdot 10^6$. The tube was connected via a 25.6 m long RG-58 cable to a fast amplifier having a rise time of 1.05 ns and a gain of 10. Two stages of such amplifiers were cascaded to get an amplification of 100. The output pulse from the amplifier was fed to a Le Croy 623 B discriminator. The discriminator output pulse width (FWHM) was set to 20 ns. We checked that variation of the output pulse width within the range from 7 to 30 ns did not affect the count rate. A 150 MHz dual scaler was used to measure the rate. The scaler was latched by 1 second wide pulses from a Rubidium clock. At first, the amplitude threshold of the discriminator was set to its lowest value (-30 mV), then it was gradually increased in steps of 5 mV during the measurement and the corresponding integral count rates were recorded for each step.

Care was taken during these measurements to ensure that the galactic plane was not in the detectors field of view.

Fig. 3a shows the measured integral amplitude spectrum of ONS. The PMT noise spectrum is also given. In fig. 3b one can see the corresponding differential amplitude spectrum (deduced from the integral one) with a well-defined single ph-e peak. One can see that the "valley" in fig. 3b lies near 50 mV, therefore, to calculate the signal one should integrate the counts of all channels above 50 mV. The same measurement was repeated on

[2]The QE of the PMT was measured with a Beckman-35 spectrophotometer, which was cross-calibrated against two large diameter calibrated photodiodes from Hamamatsu of types AE-968 and 1790, operated in the photo-voltaic mode.

two more nights with some small changes, for example, using an amplifier with a gain on only 50 or raising the HV of the tube to -2100 V, closing and opening the tube to measure the noise of the PMT and the noise due to electronic pick-up (see fig. 3c).; one could see that the photon flux of LONS was slightly different from night to night. One of the main components of the LONS ($\sim 40\%$) is air-glow or luminescence of the night sky (complex photochemical reactions of air molecules, atoms an ions in the upper atmosphere result in a continuum and line emission) and it is a decidedly dynamic phenomenon [18]. Its intensity depends on the viewing angle, increasing towards the larger zenith angles and continuously fluctuates on a time scale of a few hours and a few years about some average value (it depends on the position and activity of the Sun, the concentration of ionised particle plasma and other factors). The transparency of the atmosphere also affects these measurements.

All these measurements agreed with our data from February 1993. We found that due to the LONS our wide angle integrating detector was counting $\sim (0.97 \pm 0.06) \cdot 10^6$ Hz on a single ph-e level. When the tube was inclined at a zenith angle of ~ 30 degrees the count rate fell by $\sim 20\%$. With a further increase of zenith angle to 45 degrees the count rate dropped by a further 5%. When the tube was covered with a 2-mm thick BG-1 blue filter of the type used in AIROBICC counters, the count rate was reduced to 55% of its original value.

To calculate an integral number characterising the intensity of LONS, it is necessary to determine the average (over the LONS spectrum) quantum efficiency of the PMT. this was done by folding the quantum efficiency curve of the PMT with the typical LONS spectrum (see fig. 4), kindly provided by the astronomers of nearby William Herschel telescope [19]. We found that the average QE of the PMT between 300 and 600 mm is 8.5%. The next thing which it is necessary to know is the solid angle viewed by the detector. This we took from Monte Carlo simulations [20]. Substituting the appropriate values one obtains:

$$\mathbf{LONS_{wide\ angle}} = \frac{(0.97 \pm 0.06) \cdot 10^6)}{0.085 \cdot 0.126 sr \cdot 0.28 \cdot 10^{-4} m^2 \cdot 1s} = \mathbf{(3.2 \pm 0.2) \cdot 10^{12} ph/m^2 \cdot sr \cdot s}$$

This is the intensity of LONS for a **wide angle** detector in the wavelength range from 300 to 600 nm at mid-latitudes when directed to zenith and the galactic plane is outside of the field of view.

The LONS for a narrow angle detector. We have monitored the count rate (due to LONS) of some pixels of the imaging camera of the first Cherenkov telescope on La Palma [21]. The pixels of the camera are connected via 14 m long RG-174 then 25.6 m long RG-58 cables to amplifiers in the central control container. The amplifiers and the following electronics for the measurement of single ph-e rates were the same as those described in the previous section. The telescope was pointing to zenith.

First we measured the dependence of singe ph-e count rate upon the output pulse width of the discriminator for the chosen channel (#22). During this measurement the discriminator threshold was set to its minimum value (-30 mV) and the HV of the PMT was -1840 V, providing a gain of $1.0 \cdot 10^6$. The data are presented in fig. 5. The used discriminator was an updating one and, therefore, one should expect an exponential dependence of the measured rate from the output pulse width. An exponential fit to the

experimental data is shown on fig. 5 with the dashed line. The difference between the fit and the experimental points for the pulse widths ≤ 10 ns is because of the double pulse resolution of this discriminator is limited to ~ 9 ns. From the fit we have determined a single ph-e event rate of ~ 32 MHz. After this the pulse width of the discriminator was set to 13 ns.

Further measurements were performed during which the HV of the PMT was set to -1800 V(gain $= 0.75 \cdot 10^6$), -1900 V (gain $= 1.33 \cdot 10^6$) and -1940 V (gain $= 1.67 \cdot 10^6$). Again the threshold of the discriminator was incremented in steps of 5 to 10 mV and the corresponding integral count rates were measured. In fig. 6a are presented three integral amplitude spectra of LONS for channel #22 and in fig. 6b the three corresponding differential amplitude spectra deduced form those. The arrows on the lower part of the fig. 6b indicate the amplitude values in mV of the single ph-e peaks for corresponding distributions. These measurements were repeated with pixels #34 and #36 of the camera, giving very similar results.

We found that the channels of the camera were counting ~(20-22) MHz due to LONS. Recalling the updating feature and the pulse width of the discriminator on can estimate a single ph-e event rate of $\sim (32 \pm 2)$ MHz due to LONS. From this quantity it is easy to calculate that the mean value of charge from photo-cathode of the photo-multiplier generated by LONS is 0.9-1.0 ph-e during the ADC gate duration of 30 ns - an important number to understand the noise characteristics of the telescope.

For complete light collection in the focal plane the pixels of the camera are equipped with solid light guides made from a high UV transparency plexiglas [21]. The average (over LONS spectrum) QE of the PMT between 300 and 600 nm, optically coupled to a plexiglas light guide, is calculated to be $\sim 7.9\%$, assuming a peak QE efficiency of 19% at 400 nm. The total surface area of the telescope's reflector is 5.0 m^2 with an average reflectivity of 80%. The geometrical angular acceptance of a pixel in the camera is 0.43 degree (full angle). Now we can estimate the intensity of LONS:

$$\text{LONS} = \frac{(32 \pm 2) \cdot 10^6}{0.079 \cdot 4.4 \cdot 10^{-5} sr \cdot 0.8 \cdot 5m^2 \cdot 1s} = (2.3 \pm 0.15) \cdot 10^{12} ph/m^2 \cdot sr \cdot s$$

There could be a 10% systematic error in this number due to the ~10% uncertainty in the absolute value of the QE of the PMT.

It should be mentioned that due to the large angular acceptance of PMT modules in the camera [22] they measure not only LONS reflected by the mirrors of the telescope, but also the diffuse light reflected from the ground surrounding the telescope. The reflectivity of the ground depends on the soil type and packing, vegetation, humidity and many other factors and is gereally higher for longer wavelengths [23]. A reasonable estimate of the ground reflectivity at the telescope site is between 4 and 8%. There is a protective sheet of black polyethylene around the camera which limits the field of view to $\sim 30^\circ$ and thus lowers the stray light contribution to the signal. The pixels see the edge of the reflector at an angle of 18°. Integrating the diffuse light between 10° and 30° shows that the ground reflection contributes $\sim (25 \pm 5)\%$ to the total measured charge due to LONS. Therefore, the intensity of LONS is less by the same amount, giving

$$\text{LONS}_{\text{narrow angle}} = \mathbf{(1.75 \pm 0.4) \cdot 10^{12} ph/m^2 \cdot sr \cdot s}$$

So, this is the intensity of LONS for a **narrow angle** detector in zenith direction in the wavelength range of 300 to 600 nm at a mid-latitude site, when there are no bright stars in the field of view. The systematic error in this value comes from the above mentioned uncertainties in the values of the QE and the ground reflection. In the near future we plan to perform more direct measurement of LONS.

The estimated intensity of LONS at La Palma [24] using the results of the measurement [19], was:

$$\text{LONS} = (1.8 - 1.9 \cdot 10^{12}) ph/m^2 \cdot sr \cdot s$$

which is in reasonable agreement with our measurement. The agreement with other measurements, quoted in [9, 10, 11, 12, 13, 14, 15, 16] is also reasonable, of one tries to extrapolate their values to our spectral range and allows for the differences in measuring methods and conditions.

A method for the determination of the optical transparency of atmosphere. Here we propose a method for the determination of the optical transparency of atmosphere during repeated astrophysical measurements in the optical band. A permanent monitoring of the count rate of single ph-e due to LONS could be based on a wide angle detector (similar to the above-mentioned one). Together with the original data one would save the average rates, for example, each 5-minute interval. The high precision of such a "digital" method could provide a valuable independent information about the atmospheric transparency and temporal brightness of the night sky and could be useful during off-line analysis of data.

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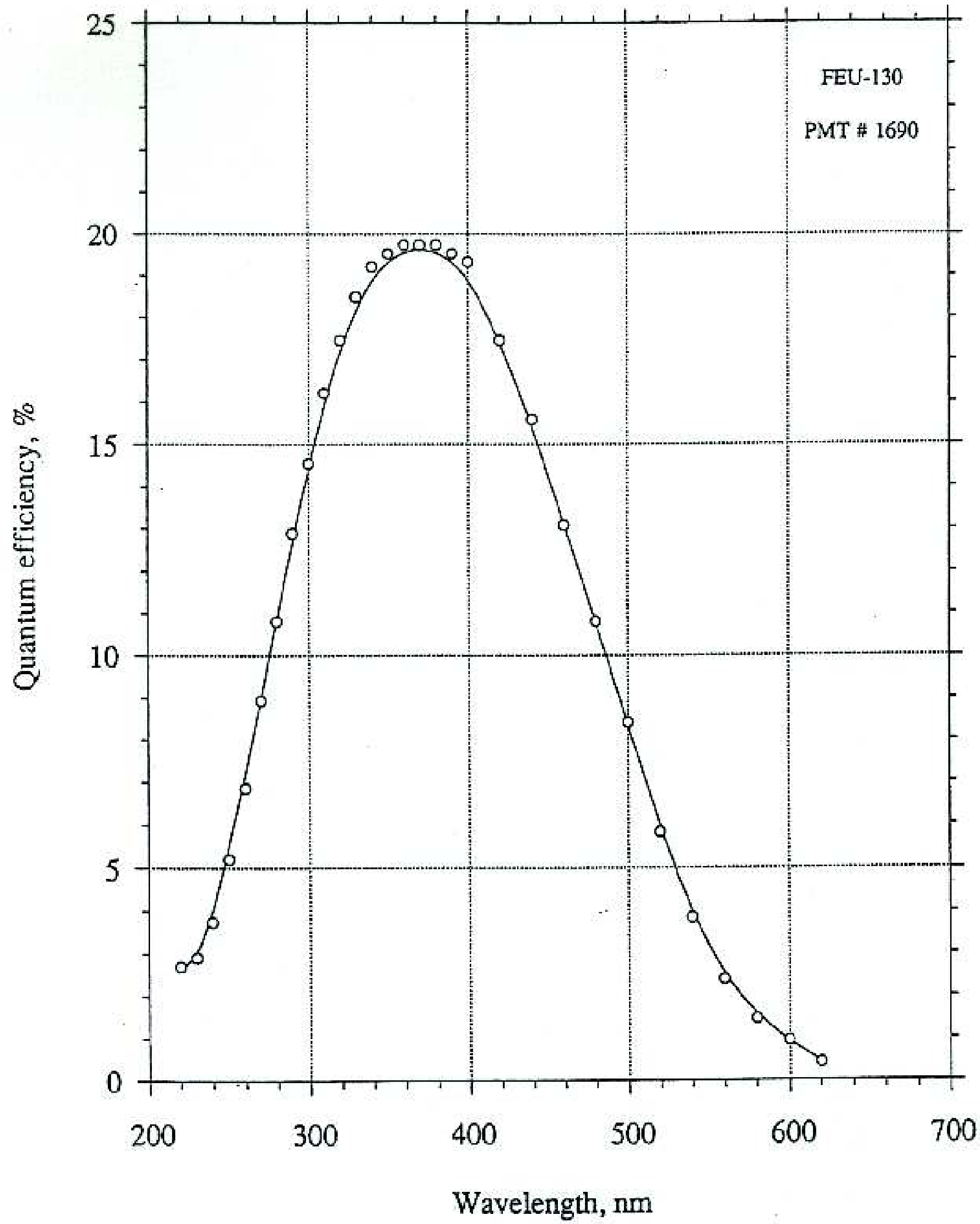

Fig. 1: The measured QE of a chosen FEU-130 PMT #1690 vs. the wavelength of illumination.

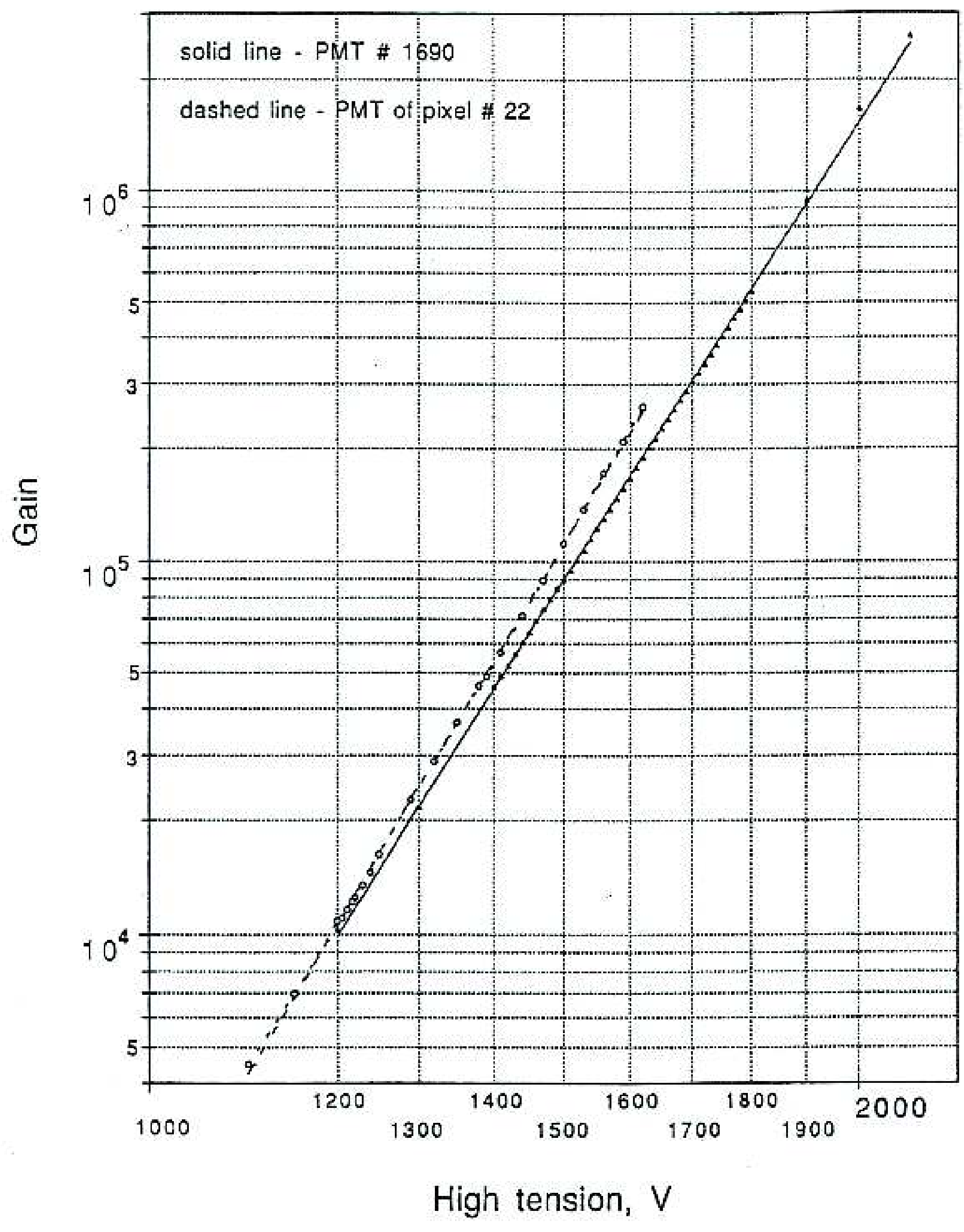

Fig. 2: The measured gains of the chosen PMTs vs. HV.

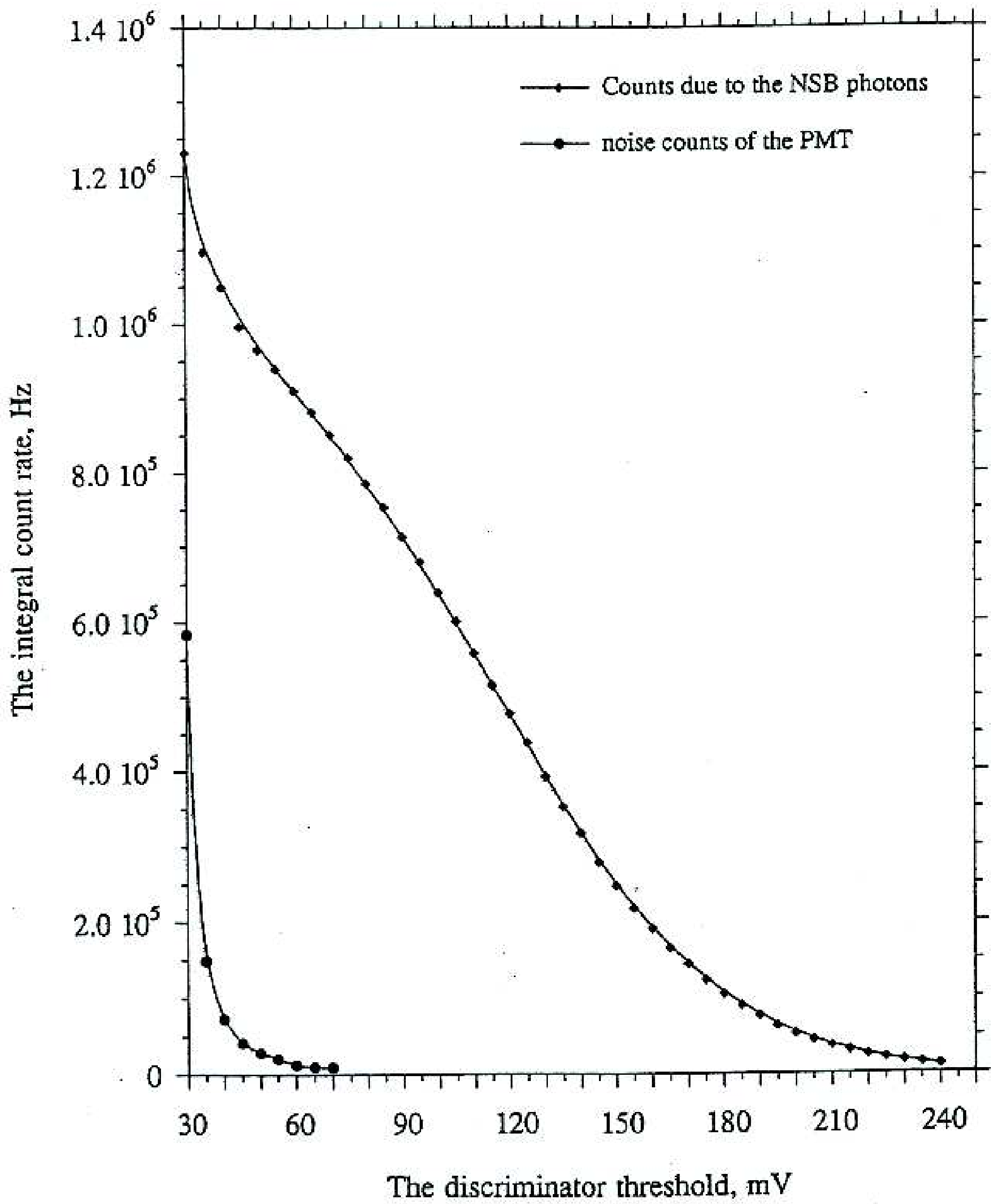

Fig. 3a: The integral amplitude spectrum of LONS measured in single ph-e mode with a wide angle integrating detector on La Palma. The PMT noise is also shown.

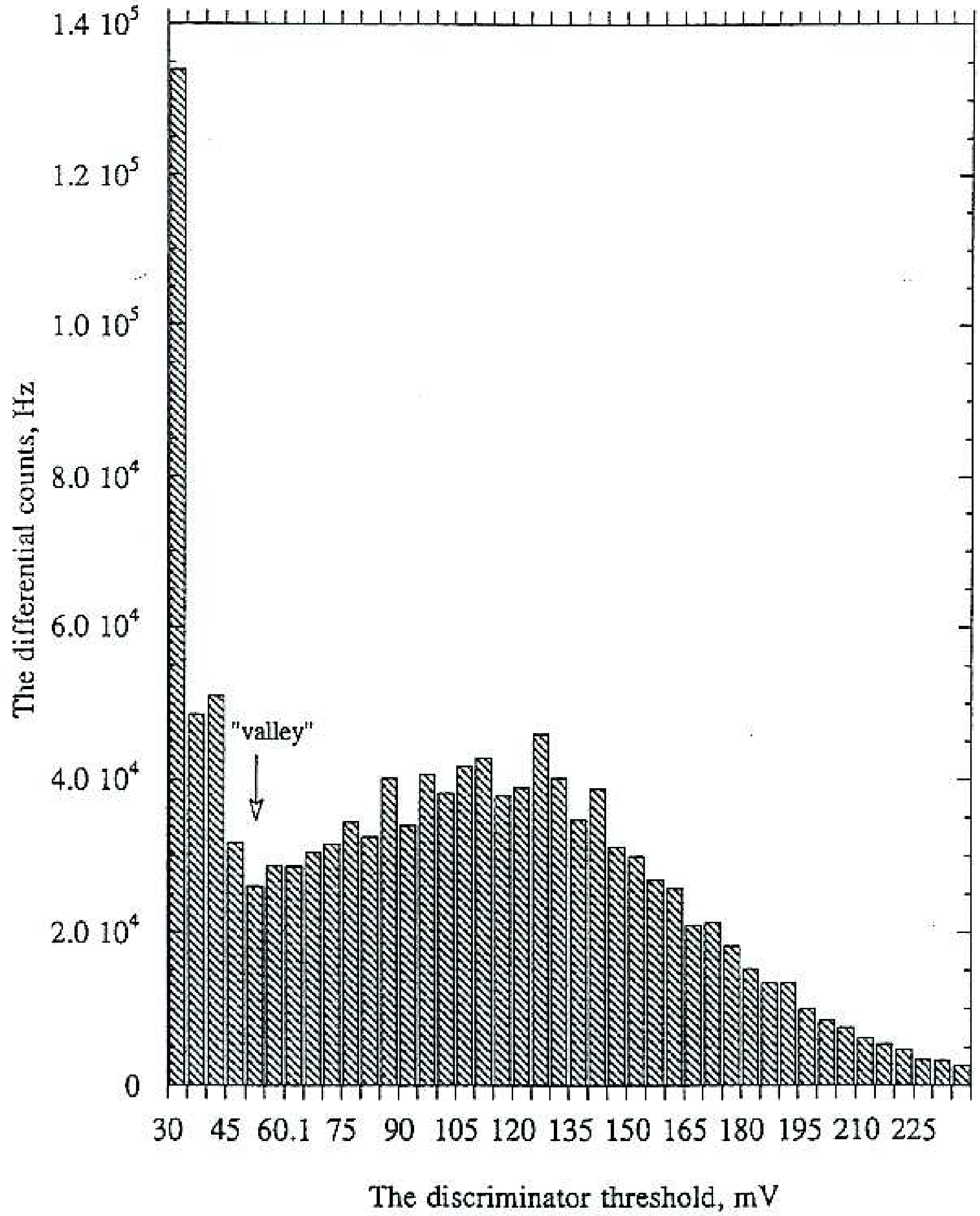

Fig. 3b: The differential amplitude spectrum of LONS, deduced from 3a.

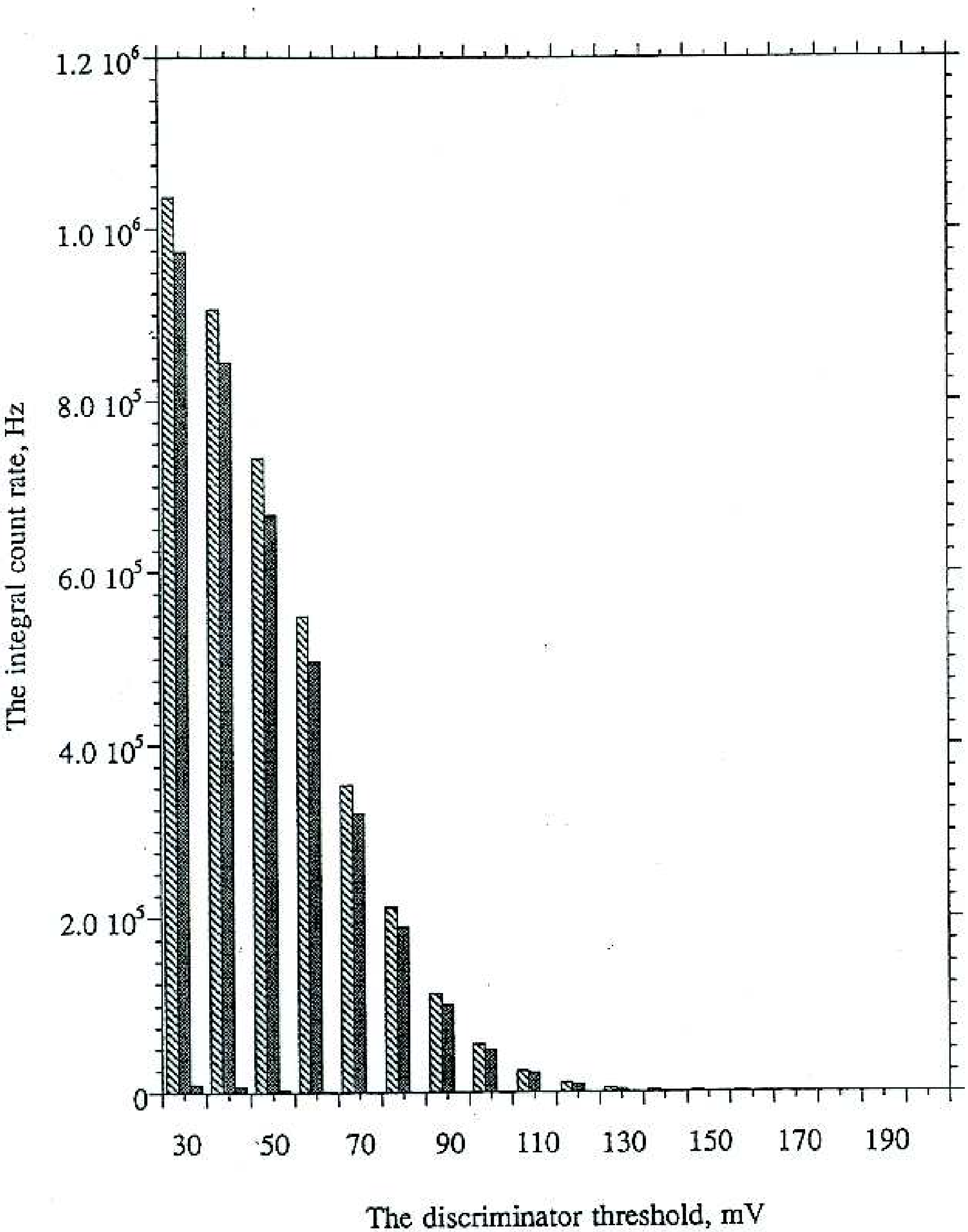

Fig. 3c: Two more measurements of the integral amplitude spectra of LONS performed on different nights. The amplifier gain is only 50. The PMT noise is shown at the lower left corner.

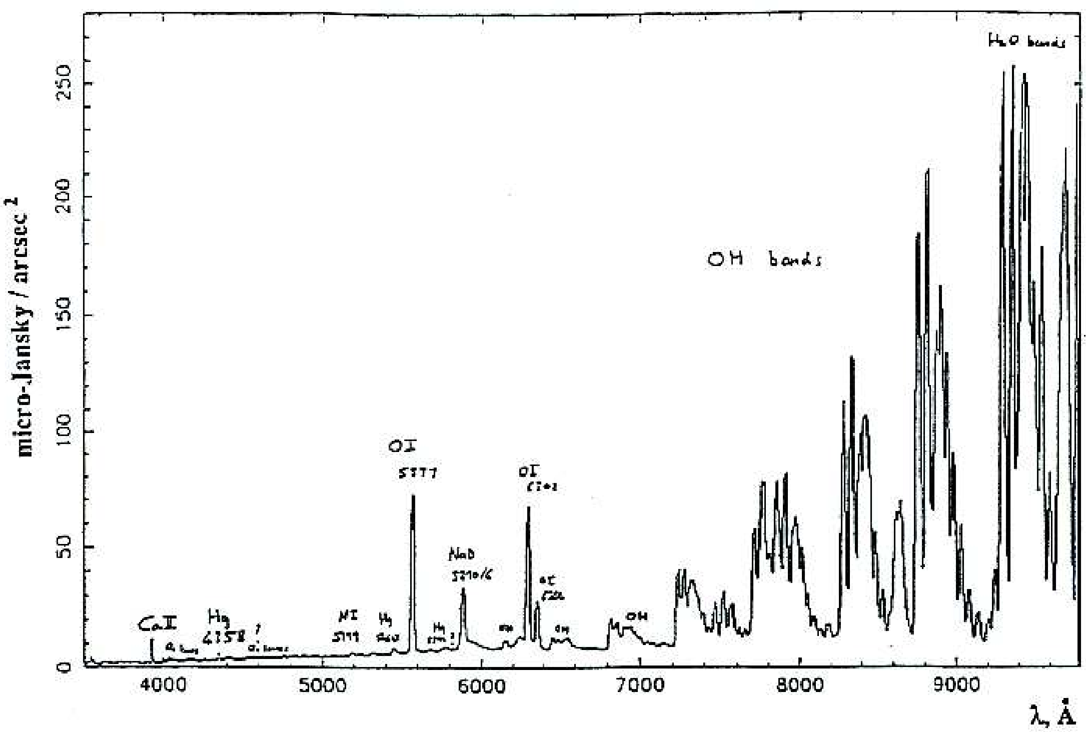

Fig. 4: A typical emission spectrum of LONS at La Palma, measured with FOS-2 spectograf at the William Herschel Telescope (after [18]).

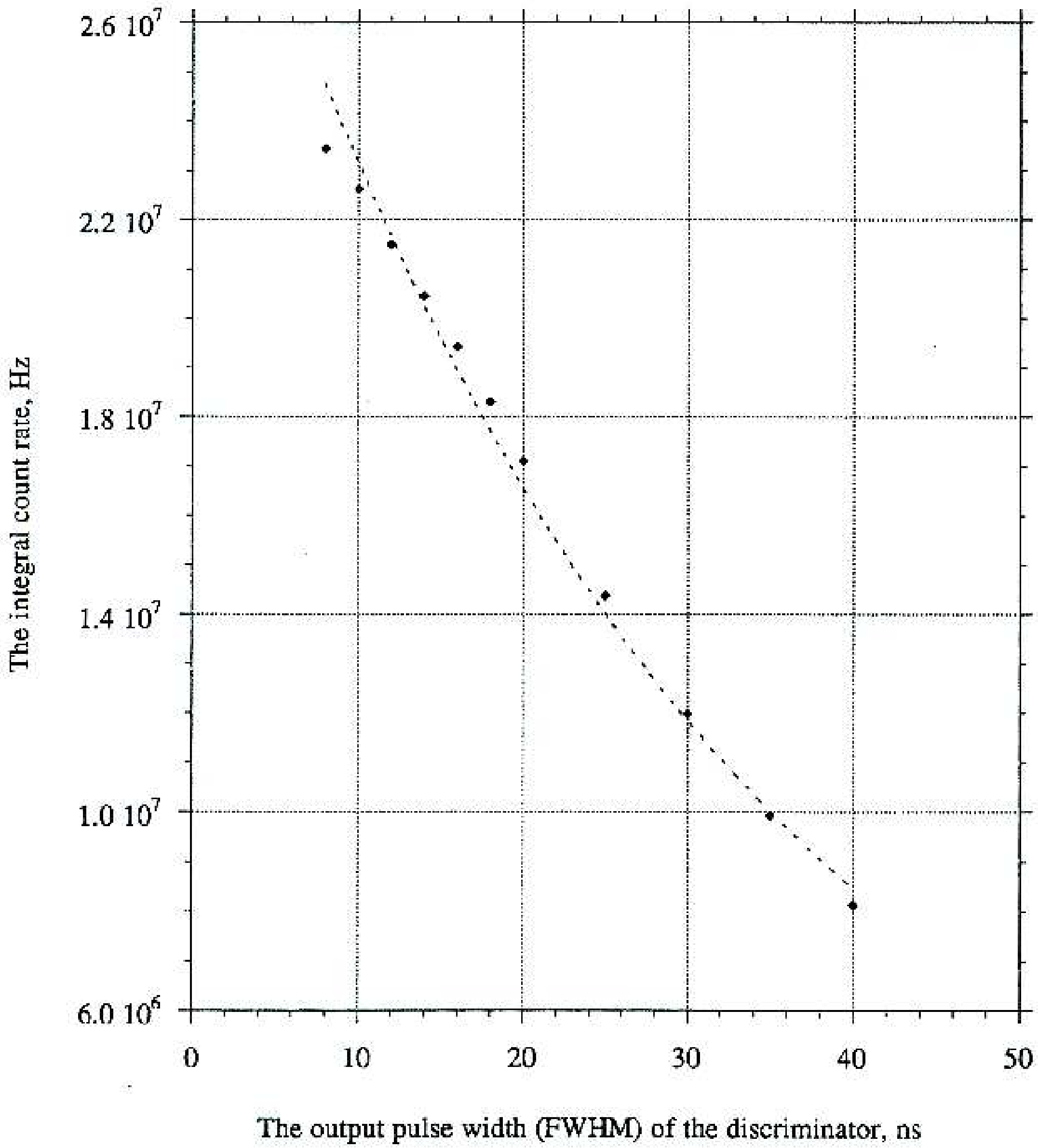

Fig. 5: The count rate of single ph-e pulses due to LONS for the telescope channel #22 versus the output pulse width of the discriminator. An exponential fit to the measured data is shown with the dashed line.

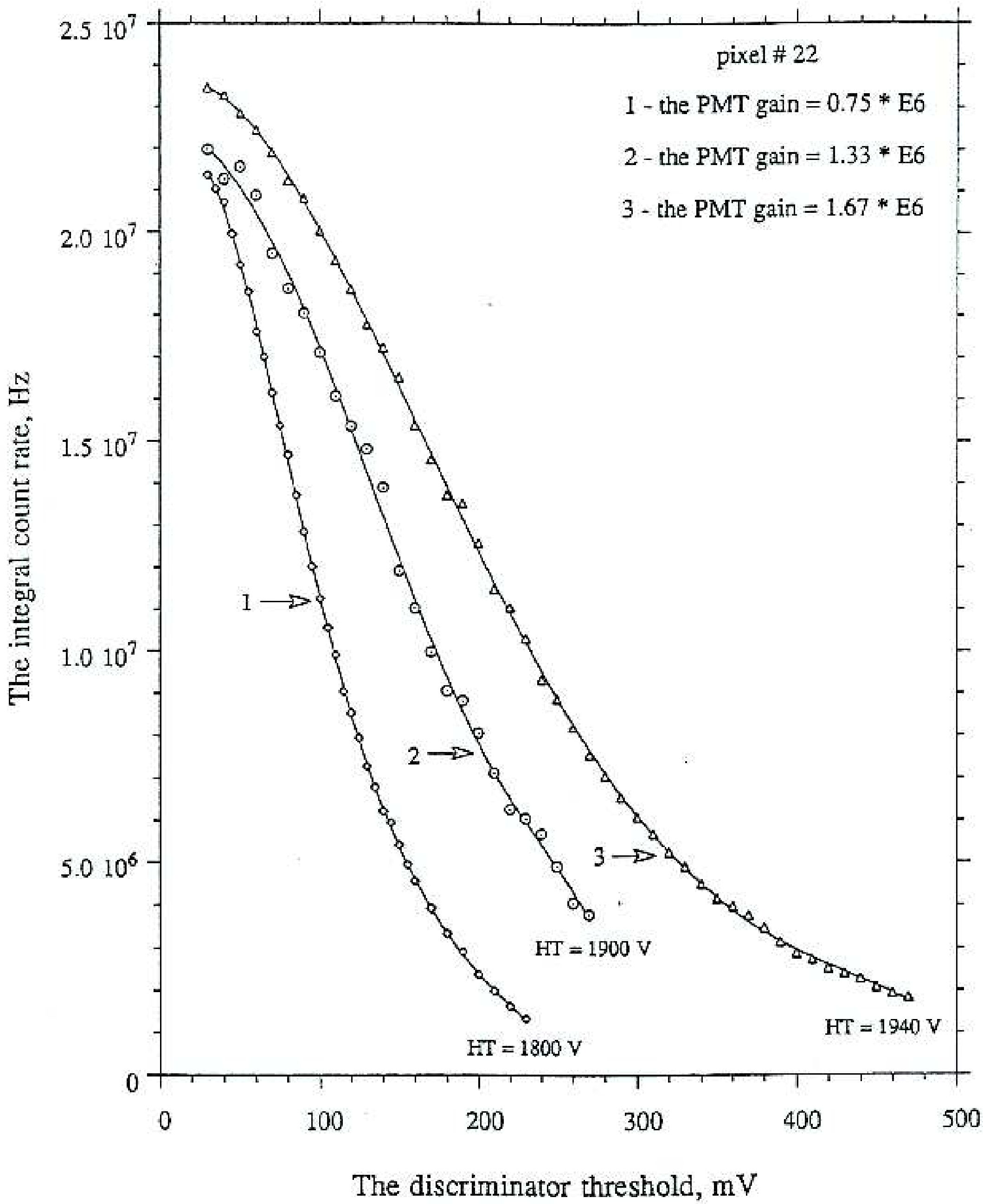

Fig. 6a: Three integral amplitude spectra of LONS measured in the single ph-e mode with the pixel #22 of the imaging camera on different nights.

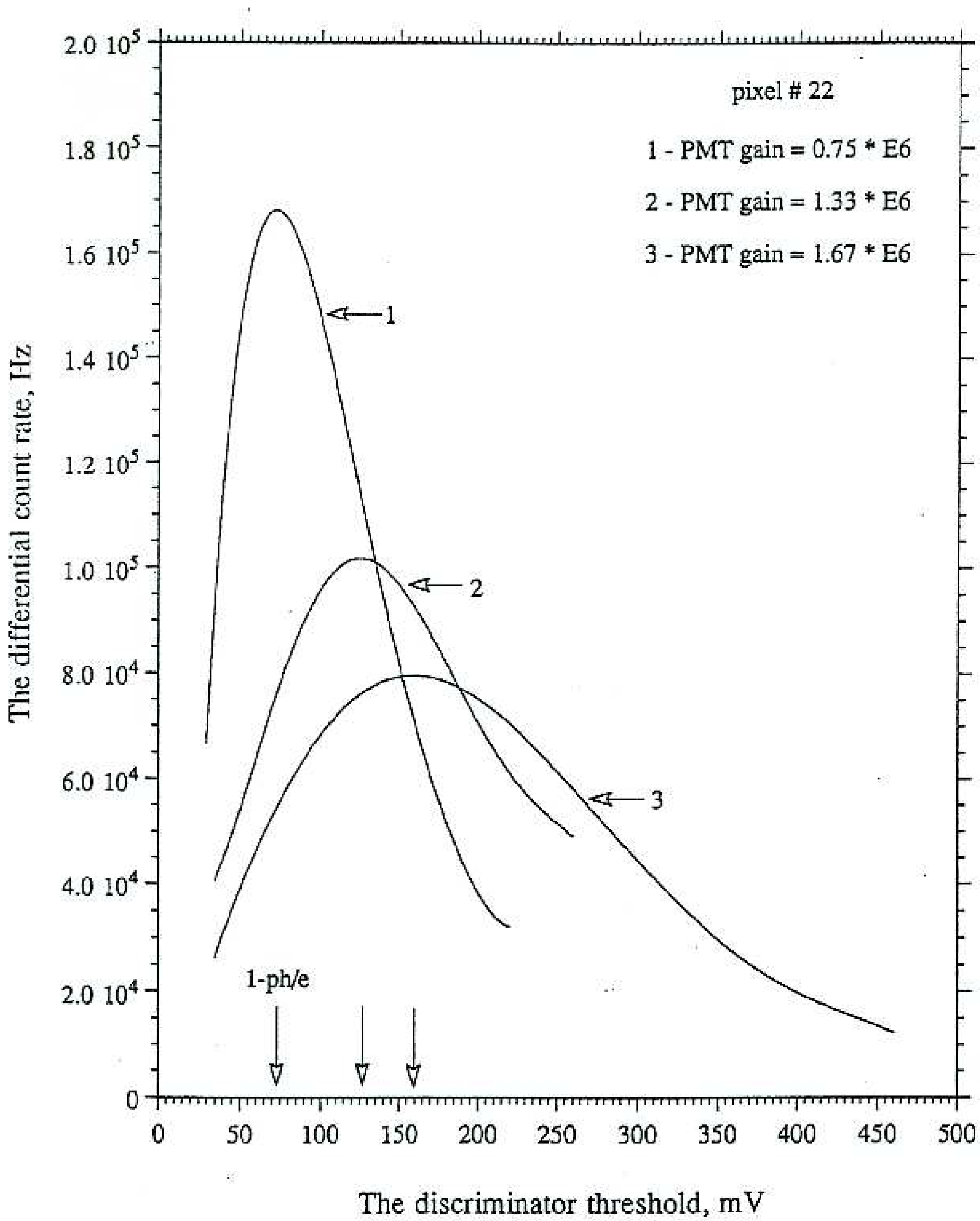

Fig. 6b: The corresponding differential amplitude spectra, deduced from 6a.